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EXPERIMENTALLY TESTING THE STANDARD COSMOLOGICAL MODEL *

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ABSTRACT

The standard model of cosmology, the big bang, is now being tested and confirmed to remarkable accuracy. Recent high precision measurements relate to (1) the microwave background; and (2) big bang nucleosynthesis. This paper focuses on the latter since that relates more directly to high energy experiments. In particular, the recent LEP (and SLC) results on the number of neutrinos are discussed as a positive laboratory test of the standard cosmology scenario. Discussion is presented on the improved light element observational data as well as the improved neutron lifetime data. Alternate nucleosynthesis scenarios of decaying matter or of quark-hadron induced inhomogeneities are discussed. It is shown that when these scenarios are made to fit the observed abundances accurately, the resulting conclusions on the baryonic density relative to the critical density, Ω_b, remain approximately the same as in the standard homogeneous case, thus, adding to the robustness of the standard model conclusion that $\Omega_b \sim 0.06$. This latter point is the driving force behind the need for non-baryonic dark matter (assuming $\Omega_{total} = 1$) and the need for dark baryonic matter, since $\Omega_{visible} < \Omega_b$. Recent accelerator constraints on non-baryonic matter are discussed, showing that any massive cold dark matter candidate must now have a mass $M_x \gtrsim 20GeV$ and an interaction weaker than the Z^0 coupling to a neutrino. It is also noted that recent hints regarding the solar neutrino experiments coupled with the see-saw model for ν-masses may imply that the ν_τ is a good hot dark matter candidate.

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Introduction

Both particle physics and cosmology have their standard models–which are getting confirmed to remarkable accuracy by the present generation of experiments. The particle model is $SU_3 \times SU_2 \times U_1$ and the cosmological model is the hot big bang.

While Hubble's work in the 1920's established an expanding universe, the establishment of modern physical cosmology and the hot big bang model hinges on two key quantitative observational tests: (1) the microwave background, and (2) big bang nucleosynthesis (BBN) and the light element abundances. This paper will focus on the second of these since that is more directly connected to high energy physics. However, it is worth noting that just as the new COBE[1] results have given renewed confidence in the $3K$ background argument, the LEP collider (along with the SLC) has given us renewed confidence in the BBN arguments. We will return to this point momentarily. Note also that the microwave background probes events at temperatures $\sim 10^4 K$ and times of $\sim 10^5$ years, whereas the light element abundances probe the Universe at temperatures $\sim 10^{10} K$ and times of ~ 1 sec. Thus, it is the nucleosynthesis results that played the most significant role in leading to the particle-cosmology merger that has taken place this past decade.

Since the popular press sometimes presents misleading headlines implying *doubts* about the big bang, it is important to note here that the real concerns referred to in these articles are really in regard to observations related to models of galaxy and structure formation. The basic hot big bang model itself is in fantastic shape with high accuracy confirmations from COBE and, as we will discuss, nucleosynthesis. However, there is admittedly no fully developed model for galaxy and structure formation that fits all of the observations. (But, of course, there is also no fully developed first principles model for star formation either.) That we might not really know exactly how to make galaxies and large-scale structure in no way casts doubt on the hot, dense early universe which we call the big bang. (We also have trouble predicting earthquakes and tornadoes, but that hasn't meant that we question celestial mechanics or a round Earth.)

Before going into the specific argument as to the relationship of BBN to LEP and the current standing of the abundance arguments as well as alternative models, let us review the history of BBN. This will draw heavily on other recent conference proceedings[2]

History of Big Bang Nucleosynthesis

It should be noted that there is a symbiotic connection between BBN and the $3K$ background dating back to Gamow and his associates Alpher and Herman. The initial BBN calculations of Gamow and his associates[3] assumed pure neutrons as an initial condition and thus were not particularly accurate, but their inaccuracies had little effect on the group's predictions for a background radiation.

Once Hayashi recognized in 1950 the role of neutron-proton equilibration, the framework for BBN calculations themselves has not varied significantly. The work of Alpher, Follin and Herman[4] and Taylor and Hoyle[5], preceeding the discovery of the 3K background, and Peebles[6] and Wagoner, Fowler and Hoyle,[7] immediately following the discovery, and the more recent work of our group of collaborators[8,9,10,11,12] all do essentially the same basic calculation, the results of which are shown in Figure 1. As far as the calculation itself goes, solving the reaction network is relatively simple by the standards of explosive nucleosynthesis calculations in supernovae (c.f. the 1965 calculation of Truran *et al.*),[13] with the changes over the last 25 years being mainly in terms of more recent

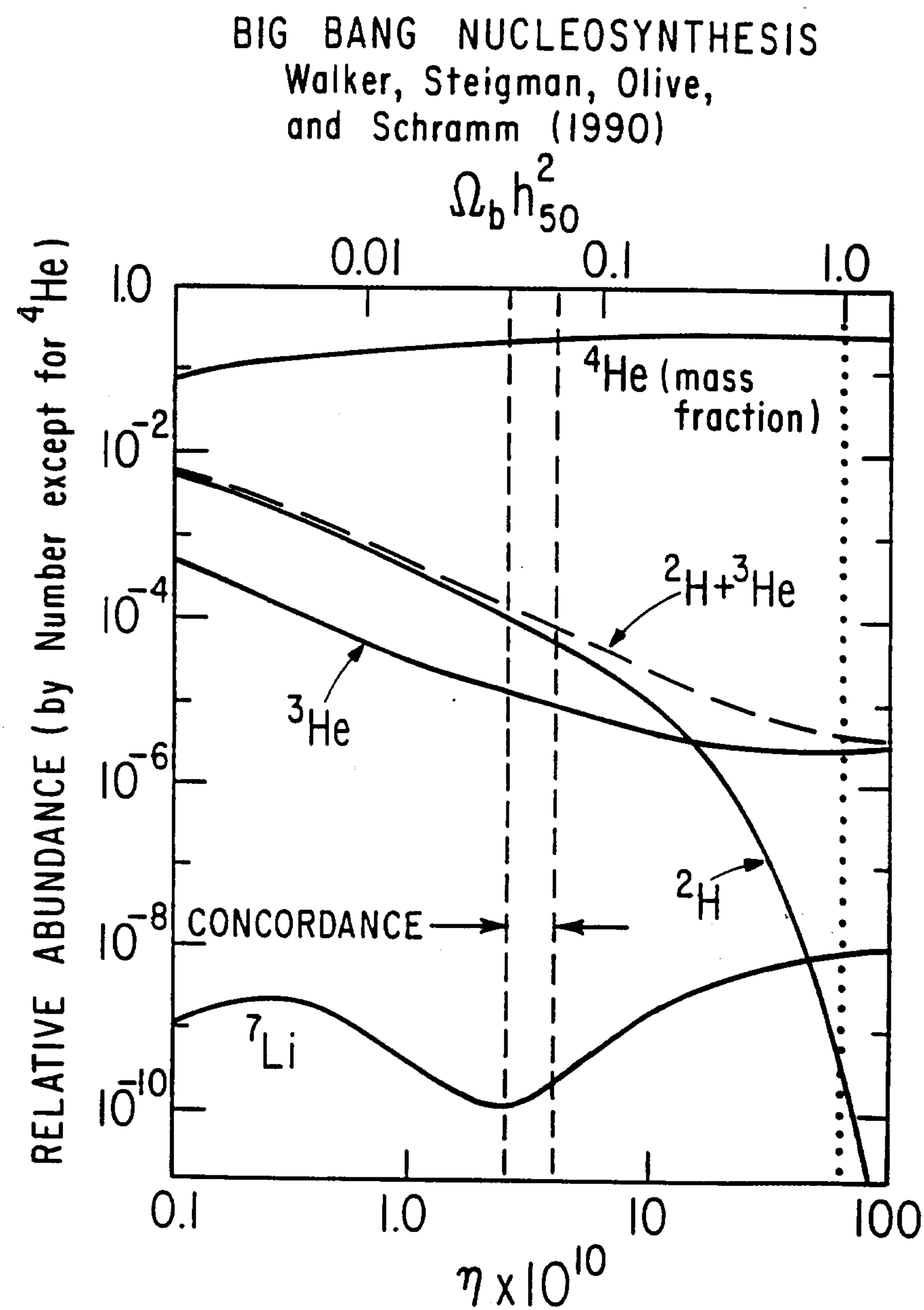

Figure 1. BBN abundances versus the baryon to photon ratio, η, or equivalently the fraction of the critical density, Ω_b.

nuclear reaction rates as input, not as any great calculational insight (although the current Kawano/Walker code[11,12] is somewhat streamlined relative to the earlier Wagoner code[7].) With the possible exception of ^7Li yields, the reaction rate changes over the past 25 years have not had any major affect.[9,11,12,13] The one key improved input is a better neutron lifetime determination, a point to which we will also shortly.

With the exception of the effects of elementary particle assumptions to which we will also return, the real excitement for BBN over the last 25 years has not really been in redoing the basic calculation. Instead, the true action is focused on understanding the evolution of the light element abundances and using that information to make powerful conclusions. In particular, in the 1960's, the main focus was on ^4He which is very insensitive to the baryon density. The agreement between BBN predictions and observations helped support the basic big bang model but gave no significant information at that time with regard to density. In fact, in the mid-1960's, the other light isotopes (which are, in principle, capable of giving density information) were generally assumed to have been made during the T-Tauri phase of stellar evolution,[15] and so, were not then taken to have cosmological significance. It was during the 1970's that BBN fully developed as a tool for probing the Universe. This possibility was in part stimulated by Ryter *et al.*[16] who showed that the T-Tauri mechanism for light element synthesis failed. Furthermore, ^2H abundance determinations[17,18] improved significantly with solar wind measurements and the interstellar work from the Copernicus satellite. Reeves, Audouze, Fowler and Schramm[19] argued for cosmological ^2H and were able to place a constraint on the baryon density excluding a universe closed with baryons. Subsequently, the ^2H arguments were cemented when Epstein, Lattimer and Schramm[20] proved that no realistic astrophysical process other than the big bang could produce significant ^2H. It was also interesting that the baryon density implied by BBN was in good agreement with the density implied by the dark galactic halos.[21]

By the late 1970's, a complimentary argument to ^2H had also developed using ^3He. In particular, it was argued[22] that, unlike ^2H, ^3He was made in stars; thus, its abundance would increase with time. Since ^3He like ^2H monotonically decreased with cosmological baryon density, this argument could be used to place a lower limit on the baryon density[23] using ^3He measurements from solar wind[17] or interstellar determinations.[24] Since the bulk of the ^2H was converted in stars to ^3He, the constraint was shown to be quite restrictive.[9] Support for this point[25] also comes from the observation of ^3He in horizontal branch stars which, as processed stars still having ^3He on their surface, indicates the survivability of ^3He.

It was interesting that the lower boundary from ^3He and the upper boundary from ^2H yielded the requirement that ^7Li be near its minimum of $^7Li/H \sim 10^{-10}$, which was verified by the Pop II Li measurements of Spite and Spite,[26] hence, yielding the situation emphasized by Yang *et al.*[9] that the light element abundances are consistent over nine orders of magnitude with BBN, but only if the cosmological baryon density is constrained to be around 6% of the critical value. It is worth noting that ^7Li alone gives both an upper and a lower limit to Ω_b. However, while its derived upper limit is more than competitive with the ^2H limit, the ^7Li lower limit is not nearly as restictive as the $^2H +^3 He$ limit. Claims that big bang nucleosynthesis can yield Ω_b lower than 0.01 must necessarily neglect the $^3He +^2 H$ limit.

The other development of the 70's for BBN was the explicit calculation of Steigman, Schramm and Gunn.[27] showing that the number of neutrino generations. N_ν, had to be small to avoid overproduction of ^4He. This will subsequently be referred to as the SSG limit.(Earlier work had noted a dependency of the ^4He abundance on assumptions about the fraction of the cosmological stress-energy in exotic particles,[28,5] but had not actually made an explicit calculation probing the quantity of interest to particle physicists. N_ν.) To put this in perspective, one should remember that the mid-1970's also saw the discovery of charm. bottom and tau, so that it almost seemed as if each new detector produced new particle discoveries. and yet, cosmology was arguing against this "conventional" wisdom. Over the years the SSG limit on N_ν improved with ^4He abundance measurements. neutron lifetime measurements and with limits on the lower bound to the baryon density; hovering at $N_\nu \lesssim 4$ for most of the 1980's and dropping to slightly lower than 4[29,30,10] just before LEP and SLC turned on.

Big Bang Nucleosynthesis: Ω_b and N_ν

The power of Big Bang Nucleosynthesis comes from the fact that essentially all of the physics input is well determined in the terrestrial laboratory. The appropriate temperature regimes, 0.1 to $1MeV$, are well explored in nuclear physics labs. Thus, what nuclei do under such conditions is not a matter of guesswork, but is precisely known. In fact, it is known for these temperatures far better than it is for the centers of stars like our sun. The center of the sun is only a little over $1keV$, thus. below the energy where nuclear reaction rates yield significant results in laboratory experiments, and only the long times and higher densities available in stars enable anything to take place.

To calculate what happens in the big bang, all one has to do is follow what a gas of baryons with density ρ_b does as the universe expands and cools. As far as nuclear reactions are concerned, the only relevant region is from a little above $1MeV$ ($\sim 10^{10}K$) down to a little below $100keV$ ($\sim 10^9 K$). At higher temperatures. no complex nuclei other than free single neutrons and protons can exist, and the ratio of neutrons to protons, n/p, is just determined by

$$n/p = e^{-Q/T},$$

where $Q = (m_n - m_p)c^2 \sim 1.3MeV$.
Equilibrium applies because the weak interaction rates are much faster than the expansion of the universe at temperatures much above $10^{10}K$. At temperatures much below $10^9 K$, the electrostatic repulsion of nuclei prevents nuclear reactions from proceeding as fast as the cosmological expansion separates the particles.

Because of the equilibrium existing for temperatures much above $10^{10}K$. we don't have to worry about what went on in the universe at higher temperatures. Thus, we can start our calculation at $10MeV$ and not worry about speculative physics like the theory of everything (T.O.E.), or grand unifying theories (GUTs), as long as a gas of neutrons and protons exists in thermal equilibriuim by the time the universe has cooled to $\sim 10MeV$.

After the weak interaction drops out of equilibrium. a little above $10^{10}K$, the ratio of neutrons to protons changes more slowly due to free neutrons decaying to protons, and similar transformations of neutrons to protons via interactions with the ambient leptons. By the time the universe reaches $10^9 K$ ($0.1MeV$), the ratio is slightly below 1/7. For temperatures above $10^9 K$, no significant abundance of complex nuclei can exist due to the continued existence of gammas with greater than MeV energies. Note that the high photon to baryon ratio in the universe ($\sim 10^{10}$) enables significant population of the MeV high energy Boltzman tail until $T \lesssim 0.1\ MeV$.

Once the temperature drops to about $10^9 K$, nuclei can exist in statistical equilibrium through reactions such as $n + p \leftrightarrow {}^2H + \gamma$ and ${}^2H + p \leftrightarrow {}^3He + \gamma$ and ${}^2H + n \leftrightarrow {}^3H + \gamma$, which in turn react to yield ${}^4He$. Since ${}^4He$ is the most tightly bound nucleus in the region, the flow of reactions converts almost all the neutrons that exist at $10^9 K$ into ${}^4He$. The flow essentially stops there because there are no stable nuclei at either mass-5 or mass-8. Since the baryon density at big bang nucleosynthesis is relatively low (much less than $1 g/cm^3$) and the time-scale short ($t \lesssim 10^2 sec$), only reactions involving two-particle collisions occur. It can be seen that combining the most abundant nuclei, protons and ${}^4He$ via two body interactions always leads to unstable mass-5. Even when one combines ${}^4He$ with rarer nuclei like ${}^3H$ or ${}^3He$, we still get only to mass-7, which, when hit by a proton, the most abundant nucleus around, yields mass-8. (A loophole around the mass-8 gap can be found if $n/p > 1$, so that excess neutrons exist, but for the standard case $n/p < 1$). Eventually, ${}^3H$ radioactively decays to ${}^3He$, and any mass-7 made radioactively decays to ${}^7Li$. Thus, big bang nucleosynthesis makes ${}^4He$ with traces of ${}^2H$, ${}^3He$, and ${}^7Li$. (Also, all the protons left over that did not capture neutrons remain as hydrogen.) For standard homogeneous BBN, all other chemical elements are made later in stars and in related processes. (Stars jump the mass-5 and -8 instability by having gravity compress the matter to sufficient densities and have much longer times available so that three-body collisions can occur.) With the possible exception of ${}^7Li$,[9,10,11,12,14] the results are rather insensitive to the detailed nuclear reaction rates. This insensitivity was discussed in ref. [9] and most recently using a Monte Carlo study by Krauss and Romanelli[14] An n/p ratio of $\sim 1/7$ yields a ${}^4He$ primordial mass fraction,

$$Y_p = \frac{2n/p}{n/p + 1} \approx \frac{1}{4}$$

The only parameter we can easily vary in such calculations is the density that corresponds to a given temperature. From the thermodynamics of an expanding universe we know that $\rho_b \propto T^3$; thus, we can relate the baryon density at $10^{10} K$ to the baryon density today, when the temperature is about $3K$. The problem is that we don't know today's ρ_b, so the calculation is carried out for a range in ρ_b. Another aspect of the density is that the cosmological expansion rate depends on the total mass-energy density associated with a given temperature. For cosmological temperatures much above $10^4 K$, the energy density of radiation exceeds the mass-energy density of the baryon gas. Thus, during big bang nucleosynthesis, we need the radiation density as well as the baryon density. The baryon density determines the density of the nuclei and thus their interaction rates, and the radiation density controls the expansion rate of the universe at those times. The density of radiation is just proportional to the number of types of radiation. Thus, the density of radiation is not a free parameter if we know how many types of relativistic particles exist when big bang nucleosynthesis occurred.

Assuming that the allowed relativistic particles at $1 MeV$ are photons, e, μ, and τ neutrinos (and their antiparticles) and electrons (and positrons), Figure 1 shows the BBN yields for a range in present ρ_b, going from less than that observed in galaxies to greater than that allowed by the observed large-scale dynamics of the universe. The ${}^4He$ yield is almost independent of the baryon density, with a very slight rise in the density due to the ability of nuclei to hold together at slightly higher temperatures and at higher densities, thus enabling nucleosynthesis to start slightly earlier, when the baryon to photon ratio is higher. No matter what assumptions one makes about the baryon density, it is clear that ^4He is predicted by big bang nucleosynthesis to be around 1/4 of the mass of the universe.

The SSG Limit - Cosmological Neutrino Counting

Let us now look at the connection to N_ν. Remember that the yield of ^4He is very sensitive to the n/p ratio. The more types of relativistic particles, the greater the energy density at a given temperature, and thus, a faster cosmological expansion. A faster expansion yields the weak-interaction rates being exceeded by the cosmological expansion rate at an earlier, higher temperature; thus, the weak interaction drops out of equilibrium sooner, yielding a higher n/p ratio. It also yields less time between dropping out of equilibrium and nucleosynthesis at $10^9 K$, which gives less time for neutrons to change into protons, thus also increasing the n/p ratio. A higher n/p ratio yields more ^4He. As we will see in the next section, quark-hadron induced variations[31] in the standard model also yield higher ^4He for higher values of Ω_b. Thus, such variants still support the constraint on the number of relativistic species.[32]

In the standard calculation we allowed for photons, electrons, and the three known neutrino species (and their antiparticles). However, following SSG and doing the calculation (see Figure 2) for additional species of neutrinos, we can see when ^4He yields exceed observational limits while still yielding a density consistent with the ρ_b bounds from ^2H, ^3He, and now ^7Li. (The new ^7Li value gives approximately the same constraint on ρ_b as the others, thus strengthening the conclusion.) The bound on ^4He comes from observations of helium in many different objects in the universe. However, since ^4He is not only produced in the big bang but in stars as well, it is important to estimate what part of the helium in some astronomical object is primordial—from the big bang—and what part is due to stellar production after the big bang. The pioneering work of the Peimberts[33] showing that ^4He varies with oxygen has now been supplemented by examination of how ^4He varies with nitrogen and carbon. The observations have also been systematically reexamined by Pagel[34]. The conclusions of Pagel[34], Steigman *et al.*[35] and Walker *et al.*[11] all agree that the ^4He mass fraction, Y_p, extrapolated to zero heavy elements, whether using N, O, or C, is $Y_p \sim 0.23$ with an upper bound allowing for possible systematics of 0.24.

The other major uncertainty in the ^4He production used to be the neutron lifetime. However, the new world average of $\tau_n = 890 \pm 4s (\tau_{1/2} = 10.3\ min)$ is dominated by the dramatic results of Mampe *et al.*[36] using a neutron bottle. This new result is quite consistent with a new counting measurement of Byrne *et al.*[37] and within the errors of the previous world average of $896 \pm 10s$ and is also consistent with the precise C_A/C_V measurements from PERKEO[38] and others. Thus, the old ranges of $10.4 \pm 0.2\ min$, used for the half-life in calculations,[39,9] seem to have converged towards the lower side. The convergence means that, instead of the previous broad bands for each neutrino flavour, we obtain relatively narrow bands (see Figure 2). Note that $N_\nu = 4$ is excluded. In fact, the SSG limit is now $N_\nu < 3.4$.[10,11]

The recent verification of this cosmological standard model prediction by LEP, $N_\nu = 2.98 \pm 0.06$, from the average of ALEPH, DELPHI, L3 and OPAL[40] collaborations as well

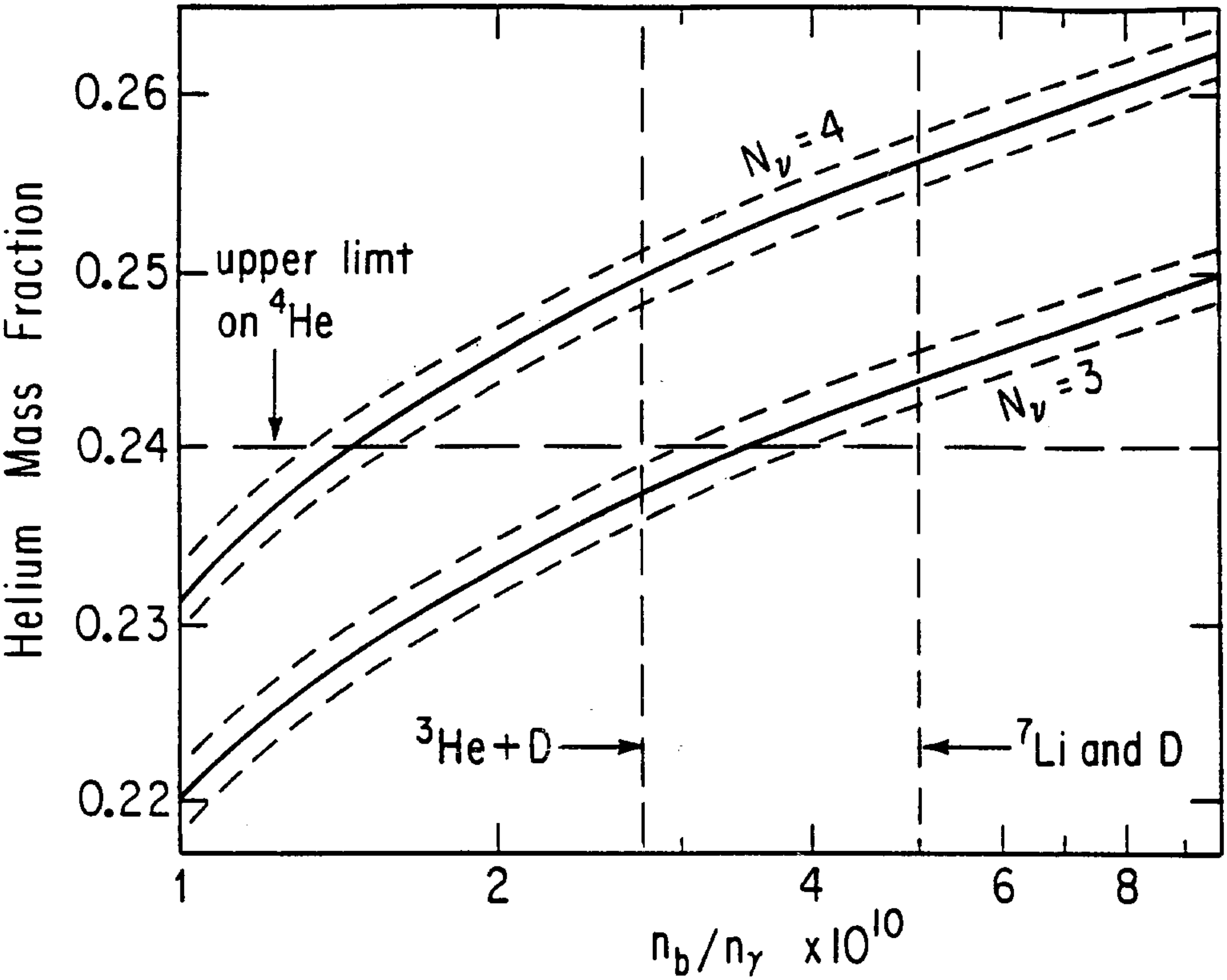

Figure 2. The SSG argument with recent parameter constraints showing the BBN helium mass fraction versus η for $N_\nu = 3$ and 4. Note that 4 is excluded.

as the SLC[40] results, thus, experimentally confirms our confidence in BBN. (However, we should also remember that LEP and cosmology are sensitive to different things.[41] Cosmology counts all relativistic degrees of freedom for $m_x \lesssim 10 MeV$, with LEP and SLC counting particles coupling to the Z^0 with $m_x \lesssim 45 GeV$.

While ν_e and ν_μ are obviously counted equally in both situations, a curious loophole exists for ν_τ since the current experimental limit $m_{\nu_\tau} < 35 MeV$ could allow it not to contribute as a full neutrino in the cosmology argument[42]. Proposed experiments which push the m_{ν_τ} limit down to less than a few MeV should eliminate this loophole. It might also be noted that if we assume m_{ν_τ} is light so that cosmologically $N_\nu = 3$, we can turn the argument around and use LEP to predict the primordial helium abundance ($\sim 24\%$), or even use limits on ^4He to give an upper limit on Ω_b (also $\lesssim 0.10$). Thus, LEP strengthens the argument that we need non-baryonic dark matter if $\Omega = 1$. In fact, note also that with $N_\nu = 3$, if Y_p is ever proven to be less than ~ 0.235, standard BBN is in difficulty. Similar difficulties occur if Li/H is ever found below $\sim 10^{-10}$. In other words, BBN is a falsifiable theory.

Alternative Proposals

As noted above, BBN yields all agree with observations using only one freely adjustable parameter, ρ_b. Thus, BBN can make strong statements regarding ρ_b if the observed light element abundances cannot be fit with any alternative theory. Before exploring the implications for ρ_b, let us examine alternative proposals which have arisen to try to escape the power of the homogeneous BBN conclusions.

The two alternatives that have recently received interest are:
(1) Decaying particles;[43] and
(2) Quark-hadron transition inspired inhomogeneities.[31]

The first of these notes that if a species of massive particle ($M \gtrsim few\ GeV$) were to decay after traditional BBN, it could redo nucleosynthesis. While previous decaying particle proposals had been made, the new idea[43] emphasizes the importance of the resulting hadron cascade which, they argue, will dominate the yields. While interesting results are obtained, problems with detailed abundance determinations do result. In particular, this class of models seems to predict inevitably that $^6Li/^7Li >> 1$, whereas observations show $^7Li/^6Li \gtrsim 10$. While at first this might seem fatal, it is almost avoidable by noting that ^6Li is much more fragile than ^7Li; thus, it is easy to deplete ^6Li and obtain the observed ratios. However, Brown and Schramm[44] have pointed out that for high surface temperature Pop II stars, the convective zones do not go deep enough to destroy any primordial ^6Li. Pilachowski *et al.*[45] have now looked at those specific stars and indeed find no ^6Li, again seeing $^7Li/^6Li > 10$. Therefore, unless the Brown and Schramm convection argument can be surmounted, ^6Li seems to contrain this model seriously. Steigman, Audouze and others have noted additional problems with this model for ^3He and ^2H ratios.

Let us now look at the quark-hadron inspired inhomogeniety models.[31] While inhomogeneity models had been looked at previously (c.f. ref. 9) and were found to make little difference, the quark-hadron inspired models had the added ingredient of variations in n/p ratios.

The initial claim by Applegate *et al.*, followed by a similar argument from Alcock *et al.*, that $\Omega_b \sim 1$ might be possible, created tremendous interest. Their argument was that if the quark-hadron transition was a first-order phase transition (as some preliminary lattice gauge calculations implied), then it was possible that large inhomogeneities could develop at $T \gtrsim 100 MeV$. The preferential diffusion of neutrons versus protons out of the high density regions could lead to big bang nucleosynthesis occurring under conditions with both density inhomogeneities and variable neutron/proton ratios. In the first round of calculations, it was claimed that such conditions might allow $\Omega_b \sim 1$, while fitting the observed primordial abundances of $^4He, ^2H, ^3He$ with an overproduction of ^7Li. Since ^7Li is the most recent of the cosmological abundance constraints and has a different observed abundace in Pop I stars versus the traditionally more primitive Pop II stars,[26] some argued that perhaps some special depletion process might be going on to reduce the excess ^7Li. Reeves and Audouze each argued against such processes and tried to turn the argument around and use lithium abundances to constrain the quark-hadron transition.

At first it appeared that if the lithium constraint could be surmounted, then the constraints of standard big bang nucleosynthesis might disintegrate. (Although Audouze, Reeves and Schramm emphasized that the number of parameters needed to fit the light elements was somewhat larger for these non-standard models, nonetheless, a non-trivial loophole appeared to be forming.) To further stimulate the flow through the loophole, Mullaney and Fowler showed that, in addition to looking at the diffusion of neutrons out of high density regions, one must also look at the subsequent effect of excess neutrons diffusing back into the high density regions as the nucleosynthesis goes to completion in the low density regions. (The initial calculations treated the two regions separately.) Mullaney and Fowler argued that for certain phase transition parameter values (e.g. nucleation site separations $\sim 10m$ at the time of the transition), this back diffusion could destroy much of the excess lithium. Recent work by Banerjee and Chitre (private communication) suggests that more accurate treatment of the diffusion calculation could reduce the interesting separation distance by several orders of magnitude.

However, Kurki-Suonio, Matzner, Olive and Schramm,[32] the Tokyo group,[46] and the Livermore group[47] have recently argued that in their detailed diffusion models, the back diffusion not only effects ^7Li, but also the other light nuclei as well. They find that for $\Omega_b \sim 1$, ^4He is also overproduced (although it does go to a minimum for similar parameter values as does the lithium). One can understand why these models might tend to overproduce ^4He and ^7Li by remembering that in standard homogeneous big bang nucleosynthesis, high baryon densities lead to excesses in these nuclei. As back diffusion evens out the effects of the initial fluctuation, the averaged result should approach the homogeneous value. Furthermore, it can be argued that any narrow range of parameters, such as those which yield relatively low lithium and helium, are unrealistic since in most realisitic phase transitions there are distributions of parameter values (distribution of nucleation sites, separations, density fluctuations, etc.). Therefore, narrow minima are washed out which would bring the ^7Li and ^4He values back up to their excesive levels for all parameter values with $\Omega \sim 1$. Furthermore, Adams and Freese[48] have argued that the boundary betwen the two phases may be fractal-like rather than smooth. The large surface area of a fractal-like boundary would allow more interaction between the regions and minimize exotic effects.

Figure 3 shows the results of Kurki-Suonio *et al.*[32] for varying spacing l with the constraints from the different light element abundances. Notice that the Li and even the ^4He constraint do not allow $\Omega_b \sim 1$. (The ^4He abundance constraint used in Kurki-Suonio *et al.* was a generous $Y_p \lesssim 0.25$; for the preferred $Y_p \lesssim 0.24$, the ^4He bound is about as

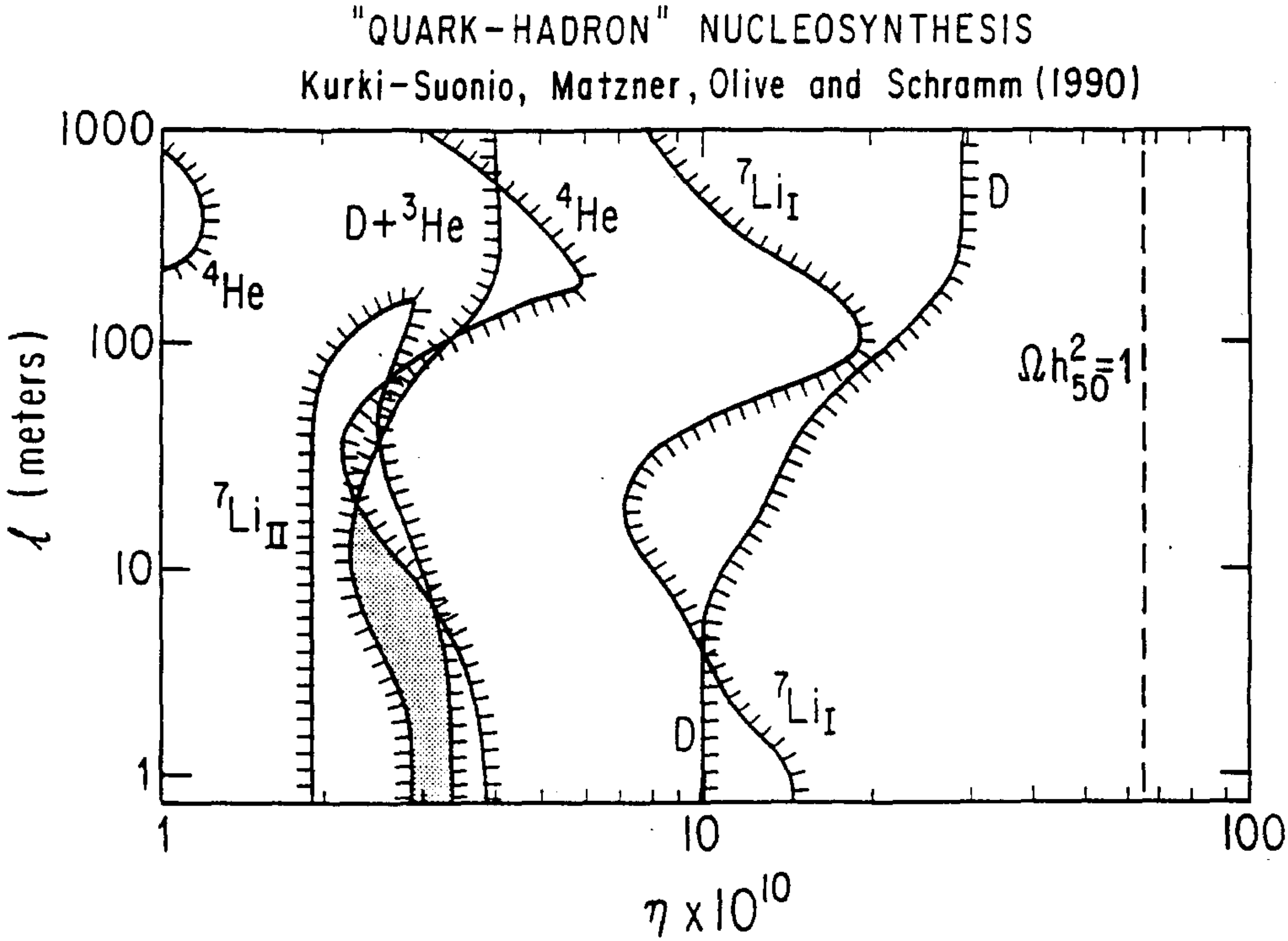

Figure 3. This shows the constraints on η of the various observed abundances in a first-order quark-hadron phase transition with nucleation sites separated by a distance l with density contrast $R \lesssim 10^3$. The Pop II lithium abundance used here is from the compilation of data given by Walker *et al.*[11] and is slightly more restrictive on η than that used in Figure 2 or used in the original Kurki-Suonio *et al.*[32] calculation from which this figure is derived. It should be noted that work by the Tokyo[46] group and by the Livermore group[47] confirms the conclusions on restricting Ω_b to values similar to the standard result even when $R \to \infty$.

tight as the Pop II Li constraint.) Note also that with the Pop II ^7Li constraint, the results for Ω_b are quite similar to the standard model with a slight excess in Ω_b possible if l is tuned to ~ 10.

Furthermore, initially it looked like quark-hadron inspired models might enable leakage[49] beyond mass-7, thus enabling ^9Be, ^{14}N, or maybe even r-process elements to become probes as whether or not the universe had such a transition (even if $\Omega_b \sim 1$). However, Tarasawa and Sato[46] have shown that when full multizone calculations of the type used by Kurki-Suonio *et al.* are utilized, then no significant leakage occurs.

One possible signature that remains for a first order quark-hadron transition is a slightly larger allowed range for Y_p that is concordant with $N_\nu = 3$ and with the other light element abundances. In particular, if ^4He were ever shown to be definitively $\lesssim 0.23$, it might be evidence for such a quark-hadron induced behavior since the standard homogenous case cannot accomodate such values. Of course, excessively low values for Y_p would still be unallowable.

One can conclude from the failure of the attempts to circumvent the standard BBN results that the results are amazingly robust. Even when many new free parameters are added, as in the quark-hadron case, the bottom line, when one requires concordance with the light element abundances, is essentially the same as the standard result. In other words, $\Omega_b \sim 0.06$ (although with fine-tuning the upper bound might be relaxed a bit to ~ 0.2 rather than 0.1).

Limits on Ω_b and Dark Matter Requirements

The narrow range in baryon density for which concordance occurs is very interesting. Let us convert it into units of the critical cosmological density for the allowed range of Hubble expansion rates. For the big bang nucleosynthesis constraints,[9,10,11,12,29,30] the dimensionless baryon density, Ω_b, that fraction of the critical density that is in baryons, is less than 0.11 and greater than 0.02 for $0.04 \lesssim h_0 \lesssim 0.7$, where h_0 is the Hubble constant in units of $100 km/sec/Mpc$. The lower bound on h_0 comes from direct observational limits and the upper bound from age of the universe constraints.[49] Note that the constraint on Ω_b means that the universe *cannot be closed with baryonic matter*. If the universe is truly at its critical density, then nonbaryonic matter is required. This argument has led to one of the major areas of research at the particle-cosmology interface, namely, the search for non-baryonic dark matter.

Another important conclusion regarding the allowed range in baryon density is that it is in very good agreement with the density implied from the dynamics of galaxies, *including their dark halos.* An early version of this argument, using only deuterium, was described over fifteen years ago.[21] As time has gone on, the argument has strengthened, and the fact remains that galaxy dynamics and nucleosynthesis agree at about 6% of the critical density. Thus, if the universe is indeed at its critical density, as many of us believe, it requires most matter not to be associated with galaxies and their halos, as well as to be nonbaryonic.

Let us put the nucleosynthetic arguments in context. The arguments requiring some sort of dark matter fall into two separate and quite distinct areas. First are the arguments using Newtonian mechanics applied to various astronomical systems that show that there is more matter present than the amount that is shining. These arguments are summarized in the first part of Table 1. It should be noted that these arguments reliably demonstrate

TABLE I

"OBSERVED" DENSITIES

$$\left[\Omega \equiv \rho/\rho_c \text{ where } \rho_c = 2 \cdot 10^{-29} h_0^2 \mathrm{g/cm^3} \text{and } h_o \equiv \frac{\mathrm{Ho}}{100 \text{ km/sec/mpc}}\right]$$

Newtonian Mechanics (cf. Faber and Gallagher[70])	
Visible	$\Omega \sim 0.007$ (factor of 2 accuracy)
Binaries Small groups Extended flat relation curves	$\Omega \sim 0.07$ (factor of 2 accuracy)
Clusters Gravitational lenses	$\Omega \sim 0.1$ to 0.3
Big Bang Nucleosynthesis (with $t_u \gtrsim 10^{10}$yrs.) (c.f. Walker *et al.*[11] and ref. therein)	$\Omega_b = 0.065 \pm 0.045$
Preliminary Large Scale Studies	
IRAS red shift study and peculiar velocities (Ref. [51])	$\Omega \gtrsim 0.3$
Density redshift counts (Loh and Spillar[71])	$\Omega \sim 1 \pm 0.6$
Inflation Paradigm (Guth[52])	$\Omega = 1$

that galactic halos seem to have a mass ~ 10 times the visible mass.

Note however that big bang nucleosynthesis requires that the bulk of the baryons in the universe are dark since $\Omega_{vis} << \Omega_b$. Thus, the dark halos could in principle be baryonic.[21] Recently arguments on very large scales[51] (bigger than cluster of galaxies) hint that Ω on those scales is indeed greater than Ω_b, thus forcing us to need non-baryonic matter. However, until these arguments are confirmed, we must look to the inflation paradigm.

This is the argument that the only long-lived natural value for Ω is unity, and that inflation[52] or something like it provided the early universe with the mechanism to achieve that value and thereby solve the flatness and smoothness problems. Thus, our need for exotica is dependent on inflation and big bang nucleosythesis and not on the existence of dark galatic halos. This point is frequently forgotten, not only by some members of the popular press but occasionally by active workers in the field.

Some baryonic dark matter must exist since from the $^2H + ^3He$ argument we know that the lower bound from big bang nucleosynthesis is greater than the upper limits on the amount of visible matter in the universe. However, we do not know what form this baryonic dark matter is in. It could be either in condensed objects in the halo, such as brown dwarfs and jupiters (objects with $\lesssim 0.08 M_\odot$ so they are not bright shining stars), or in black holes (which at the time of nucleosynthesis would have been baryons). Or, if the baryonic dark matter is not in the halo, it could be in hot intergalactic gas, hot enough not to show absorption lines in the Gunn-Peterson test, but not so hot as to be seen in the x-rays. Evidence for some hot gas is found in clusters of galaxies. However, the amount of gas in clusters would not be enough to make up the entire missing baryonic matter. Another possible hiding place for the dark baryons would be failed galaxies, large clumps of baryons that condense gravitationally but did not produce stars. Such clumps are predicted in galaxy formation scenarios that include large amounts of biasing where only some fraction of the clumps shine.

Hegyi and Olive[53] have argued that dark baryonic halos are unlikely. However, they do allow for the loopholes mentioned above of low mass objects or of massive black holes. It is worth noting that, as Schramm[2] points out, these loopholes are not that unlikely. Furthermore, recent observational evidence,[54], seems to show disk formation is relatively late, occurring at red shifts z $\lesssim$ 1. Thus, the first several billion years of a galaxy's life may have been spent prior to the formation of the disk. In fact, if the first large objects to form are less than galactic mass, as many scenarios imply, then mergers are necessary for eventual galaxy size objects. Mergers stimulate star formation while putting early objects into halos rather than disks. Mathews and Schramm[55] have recently developed a galactic evolution model which does just that and gives a reasonable scenario for chemical evolution. (This scenario also provides a natural explanation for the number-versus-redshift relation of low luminosity galaxies found by Cowie.[56] Thus, while making halos out of exotic material may be more exciting, it is certainly not impossible for the halos to be in the form of dark baryons. One application of William of Ockham's famous razor would be to have us not invoke exotic matter until we are forced to do so.

Non-baryonic matter can be divided following Bond and Szalay[57] into two major categories for cosmological purposes: hot dark matter (HDM) and cold dark matter (CDM). Hot dark matter is matter that is relativistic until just before the epoch of galaxy formation, the best example being low mass neutrinos with $m_\nu \sim 25 eV$. (Remember $\Omega_\nu \sim \frac{m_\nu(eV)}{100 h_0^2}$).

Cold dark matter is matter that is moving slowly at the epoch of galaxy formation.

Because it is moving slowly, it can clump on very small scales, whereas HDM tends to have more difficulty in being confined on small scales. Examples of CDM could be massive neutrino-like particles with masses, M_x, greater than several GeV or the lightest supersymmetric particle which is presumed to be stable and might also have masses of several GeV. Following Michael Turner, all such weakly interacting massive particles are called "WIMPS." Axions, while very light, would also be moving very slowly[58] and, thus, would clump on small scales. Or, one could also go to non-elementary particle candidates, such as planetary mass blackholes or quark nuggets of strange quark matter, possibly produced at the quark-hadron transition.[59] Another possibility would be any sort of massive toplogical remnant left over from some early phase transition. Note that CDM would clump in halos, thus requiring the dark baryonic matter to be out between galaxies, whereas HDM would allow baryonic halos.

When thinking about dark matter candidates, one should remember the basic work of Zeldovich,[60] resurrected by Lee and Weinberg[61] and others,[62] which showed for a weakly interacting particle that one can obtain closure densities, either if the particle is very light, $\sim 25eV$, or if the particle is very massive, $\sim 3GeV$. This occurs because, if the particle is much lighter than the decoupling temperature, then its number density is the number density of photons (to within spin factors and small corrections), and so the mass density is in direct proportion to the particle mass, since the number density is fixed. However, if the mass of the particle is much greater than the decoupling temperature, then annihilations will deplete the particle number since, as the temperature of the expanding universe drops below the rest mass of the particle, Boltzmann suppression prohibits production while the number is depleted via annihilations until the annihilation reacton freezes out. For normal weakly interacting particles, decoupling occurs at a temperature of $\sim 1MeV$, so higher mass particles are depleted. It should also be noted that the curve of density versus particle mass turns over again (see Figure 4) once the mass of the WIMP exceeds the mass of the coupling boson[63,64,65] so that the annihilation cross section varies as $\frac{1}{M_x^2}$, independent of the mass of the coupling boson. In this latter case, $\Omega = 1$ can be obtained for $M_x \sim 1TeV \sim (3K \times M_{Planck})^{1/2}$, where $3K$ and M_{Planck} are the only energy scales left in the calculation (see Figure 4). A loophole to this argument occurs if there is a matter-antimatter assymmetry as in the case of baryons. However, such particles would have to be Dirac particles and we will see that they are still severely constrained.

A few years ago the preferred candidate particle was probably a few GeV mass WIMP. However, LEP's lack of discovery of any new particle coupling to the Z° with $M_x \lesssim 45GeV$, coupled with underground experiments[66] clearly eliminates that candidate[67,68]. Constraints for particles not fully coupled to the Z^0 were discussed by Ellis, Nanopoulos, Roskowski and Schramm[68] and are updated and presented in Figures 5a and 5b. (The inclusion of the Kamiokande II results as well as the newer LEP limits yields an important update over the results of Ellis *et al.*[68] since it closes the loophole for Dirac particles near $12GeV$.) Note also that the generic constraints of Figure 5 also apply to other hypothetical particles since CDF and UA2 do not see any squarks, sleptons, Ẃs or Źs up to masses significantly greater than M_{Z^0}. Thus, whatever the coupling boson is, it must be greater than M_{Z^0} which means the effective value for $\sin^2 \phi_Z$ is < 1.

Furthermore, as Krauss[67] has emphasized, scaler particles such as sneutrinos interact like Dirac neutrinos so that the Kamiokande II and ionization experimental limits[66] also apply. Since asymmetric candidates are all Dirac particles, the restricted part of Figure

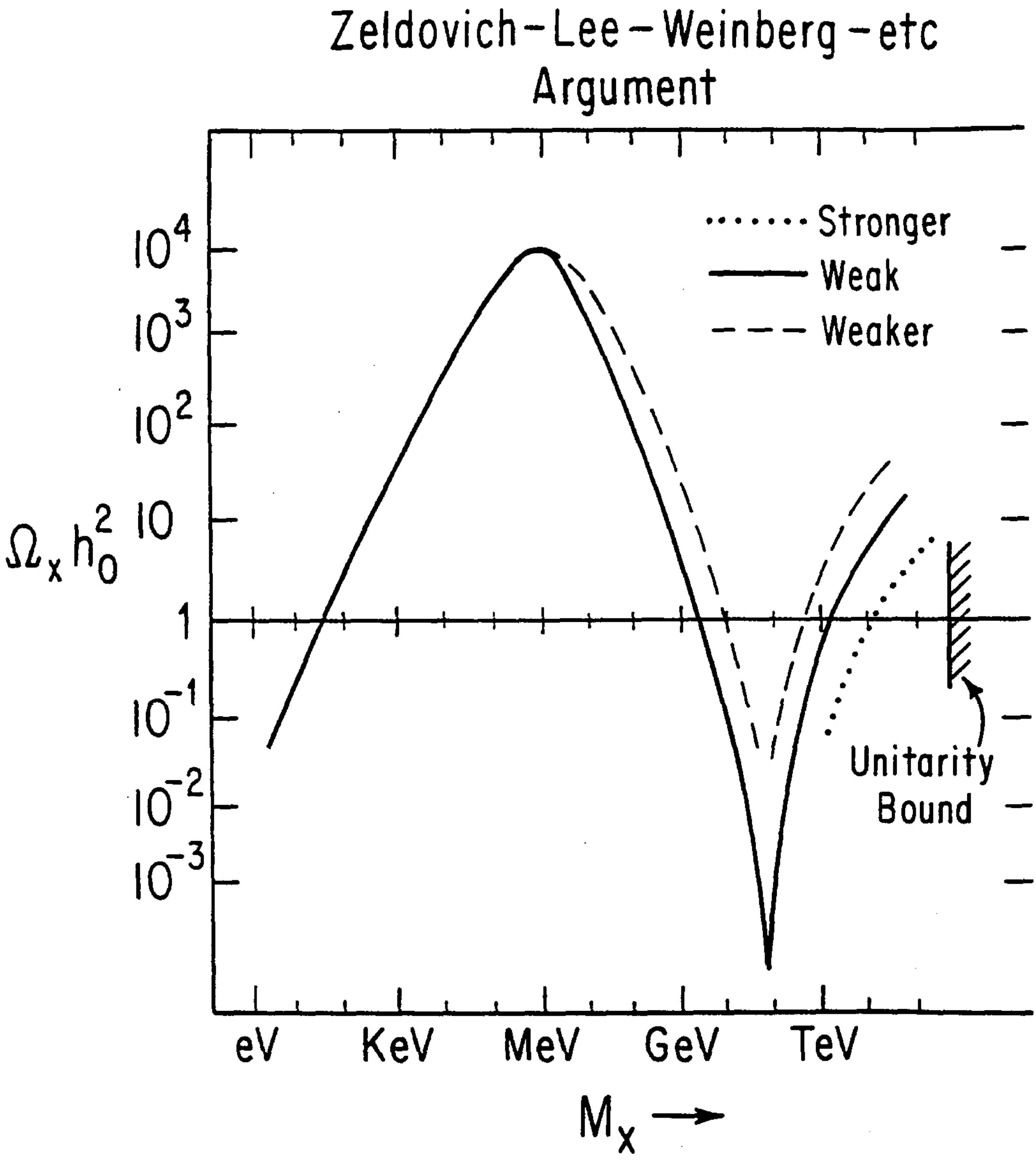

Figure 4. $\Omega_x h_0^2$ versus M_x for weakly interacting particles showing three crossings of $\Omega h_0^2 = 1$. Note also how the curve shifts at high M_x for interactions weaker or stronger than normal weak interaction (where normal weak is that of neutrino coupling through Z^0). Extreme strong couplings reach a unitarity limit at $M_x \sim 340 TeV$.

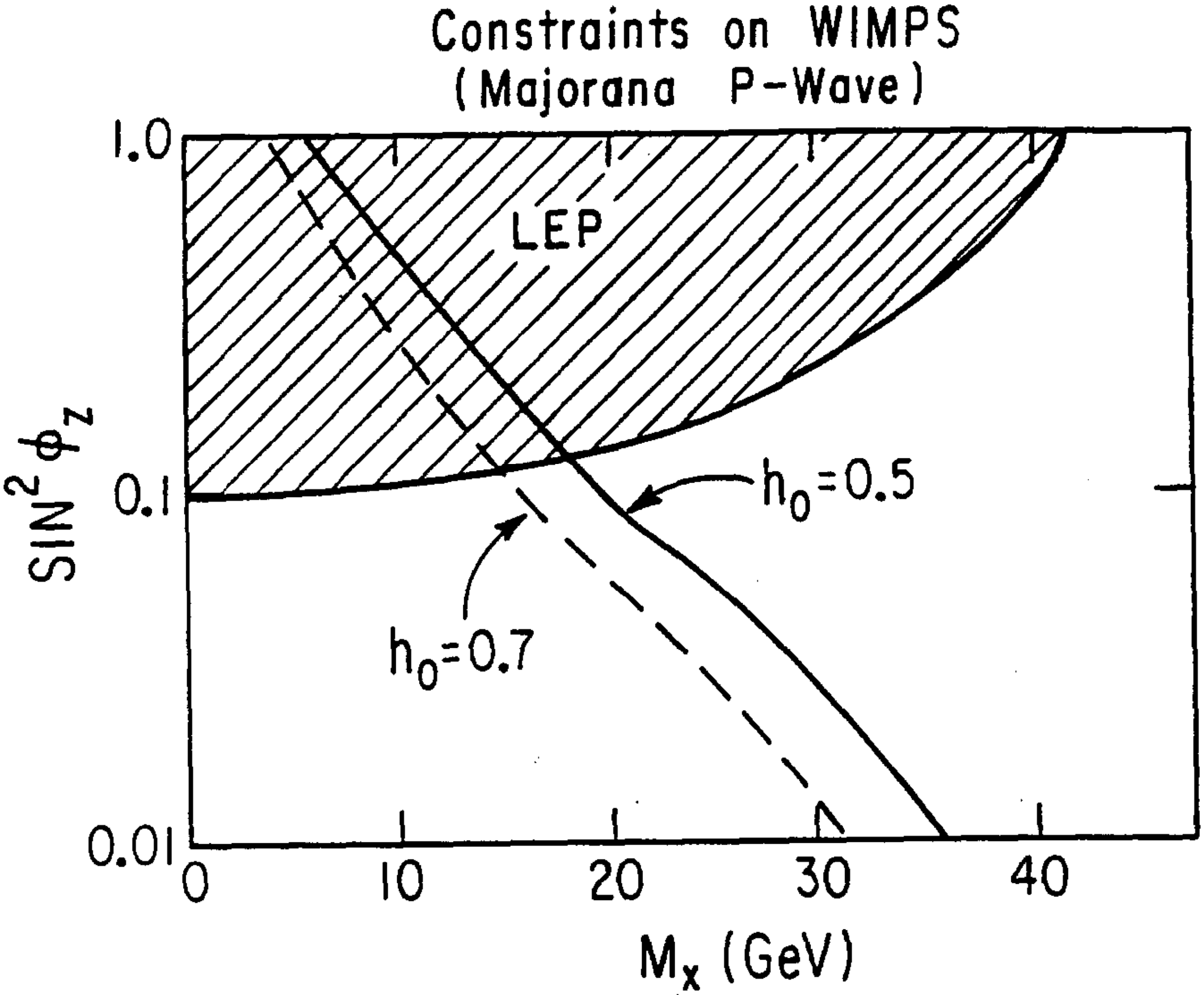

Figure 5a. Constraints on WIMPS of mass M_x versus $\sin^2\phi_z$, the relative coupling to the Z^0. The constraints are shown assuming Majorana particles (p-wave interactions). The diagonal lines show the combinations of M_x and $\sin^2\phi_z$ that yield $\Omega = 1$. The cross-hatched region is what is ruled out by the current LEP results. Note that $\Omega = 1$ with $h_0 = 0.5$ is possible only if $M_x \gtrsim 20GeV$ and $\sin^2\phi_z < 0.1$. This figure is revised from that of Ref.[68] using latest LEP results.

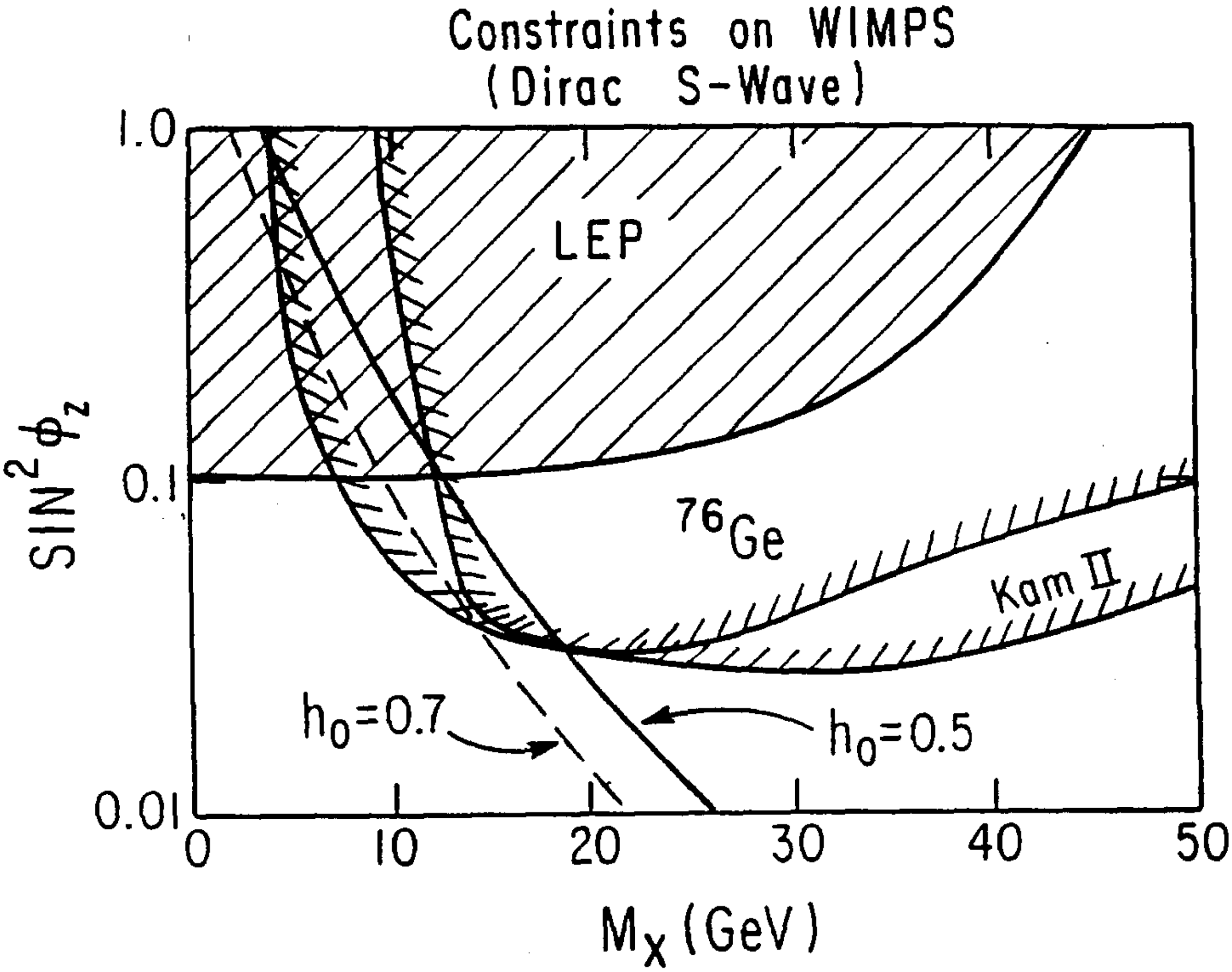

Figure 5b. This is the same as 5a but for Dirac particles (s-wave interactions). The ^{76}Ge region is that ruled out by the Caldwell *et al.* double-β decay style experiments. This figure is revised from that of Ref.[68] using latest LEP results and using new Kamiokande limits which closed a possible loophole near $M_x \sim 10 GeV$. The current results require $M_x \gtrsim 20 GeV$ and $\sin^2 \phi_z \lesssim 0.03$ for matter-antimatter symmetric particles and also exclude the entire cross hatched region for asymmetric particle candidates.

5b constrains asymmetric candidates where $\Omega = 1$ is no longer required to follow the locus shown. Thus, it seems that whether the particle is matter-antimatter symmetric or not, it is required to have an interaction weaker than weak and/or have a mass greater than about $20GeV$. Future dark matter searches should thus focus on more massive and more weakly interacting particles.

Also, as Dimopoulos[63] has emphasized, the next appealing crossing of $\Omega = 1$ (see Figure 4) is $\gtrsim 1TeV$ (but, in any case, $\lesssim 340TeV$ from the unitarity bound[65]), which can be probed by SSC and LHC as well as by underground detectors. After the correct experimental constraints are taken into account, the favoured CDM particle candidate is now either a $10^{-5}eV$ axion or a gaugino with a mass of many tens of GeV. Of course an HDM ν_τ with $m_{\nu_\tau} \sim 20 \pm 10eV$ is still a fine candidate as long as galaxy formation proceeds by some mechanism other than adiabatic gaussian matter fluctuations.[69,72] This latter candidate becomes particularly attractive if recent hints from the gallium experiment[73] require the solution to the solar neutrino problem to have neutrino mixing with $\nu_e - \nu_\mu$ mass scales of 0.01 to 0.001 eV, making multiple eV mass scales for ν_τ quite plausible from see-saw type models where $m_{\nu_\tau} \sim m_{\nu_\mu}(\frac{M_{f_3}}{M_{f_2}})^2$ and M_{f_i} is an associated fermion mass for the ith generation. For example, if one uses the heavy quark masses $(\frac{M_t}{M_c})^2 \sim 10^4$ so that ν_τ becomes ideal HDM. Such possibilities also may help late-time phase transition models for producing structure.[72]

Conclusion

We have seen that big bang nucleosynthesis has grown with time to become one of our most powerful probes of the early universe. Its resultant requirement that $N_\nu \sim 3$ has been verified in the experimental laboratory. Attempts to circumvent the standard model have ended up yielding the same conclusions, thus adding to the robustness of the result. The conclusion that $\Omega_b \sim 0.06$ is the principle argument behind non-baryonic dark matter, but the other edge of the argument is that it also requires a significant amount of baryonic dark matter. Both of these predictions will be the focus of much observational and experimental research over the coming years. Considering the success of the previous predictions of big bang nucleosynthesis, devoting a major effort to looking for dark matter, both baryonic and non-baryonic, should not be in vain.

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References

1. J. Mather *et al.*, COBE preprint, Goddard Space Flight Center *Astrophys. J.*, in press (1990).

2. D. Schramm, *Proc. of the 1990 Rencontre de Physique at La Thuile, March 1990*, ed. M. Greco, in press (1990).

   D. Schramm, *Proc. 1990 Nobel Symposium, Gräftvållen, Sweden*, in press (1990).

   D. Schramm, *Proc. of the Moriond Astrophysics Meeting on Particle Astrophysics at Les Arcs, Savoie, France, March 1990*, ed. T. Piran, in press (1990).

3. R.A. Alpher, H. Bethe and G. Gamow, *Phys. Rev.* **73** (1948) 803.

4. R.A. Alpher, J.W. Follin and R.C. Herman, *Phys. Rev.* **92** (1953) 1347.

5. R. Taylor and F. Hoyle, *Nature* **203** (1964) 1108.

6. P.J.E. Peebles, *Phys. Rev. Lett.* **16** (1966) 410.

7. P. Wagoner, W.A. Fowler and F. Hoyle, *Astrophys. J.* **148** (1967) 3.

8. D.N. Schramm and R.V. Wagoner, *Ann. Rev. of Nuc. Sci.* **27** (1977) 37.

   K. Olive, D.N. Schramm, G. Steigman, M. Turner and J. Yang, *Astrophys. J.* **246** (1981) 557;

   A. Boesgaard and G. Steigman, *Ann. Rev. of Astron. and Astrophys.* **23** (1985) 319.

9. J. Yang, M. Turner, G. Steigman, D.N. Schramm and K. Olive, *Astrophys. J.* **281** (1984) 493.

10. K. Olive, D.N. Schramm, G. Steigman and T. Walker, *Phys. Lett B.* **236** (1990) 454.

11. T. Walker, G. Steigman, D. Schramm, H.-S. Kang and K. Olive, *Astrophys. J.*, submitted (1990).

12. L. Kawano, D.N. Schramm and G. Steigman, *Astrophys. J.* **327** (1988) 750.

13. J.W. Truran, A.G. Cameron and A. Gilbert, *Canadian Journal of Physics* **44** (1966) 563.

14. L. Krauss and P. Romanelli, Yale University preprint and *Ap.J.*, in press (1990).

15. W. Fowler, J. Greenstein and F. Hoyle *Geophys. J.R.A.S.* **6**, 6 (1962).

16. C. Ryter, H. Reeves, E. Gradstajn and J. Audouze, *Astron. and Astrophys.* **8** (1970) 389.

17. J. Geiss and H. Reeves, *Astron. and Astrophys.* **18** (1971) 126;

    D. Black, *Nature* **234** (1971) 148.

18. J. Rogerson and D. York, *Astrophys. J.* **186** (1973) L95.

19. H. Reeves, J. Audouze, W.A. Fowler and D.N. Schramm, *Astrophys. J.* **179** (1973) 909.

20. R. Epstein, J. Lattimer and D.N. Schramm, *Nature* **263** (1976) 198.

21. J. R. Gott, III, J. Gunn, D.N. Schramm and B.M. Tinsley, *Astrophys. J.* **194** (1974) 543.

22. R.T. Rood, G. Steigman and B.M. Tinsley, *Astrophys. J.* **207** (1976) L57.

23. J. Yang, D.N. Schramm, G. Steigman and R.T. Rood, *Astrophys. J.* **227** (1979) 697.

24. T. Wilson, R.T. Rood and T. Bania, *Proc. of the ESO Workshop on Primordial Healing*, ed. P. Shaver and D. Knuth (Garching: European Southern Observatory, 1983).

25. M.R. Hartoog, *Ap.J.* **231** (1979) 161.

    J. Ostriker and D.N. Schramm, FNAL/Princeton preprint (1990).

26. J. Spite and F. Spite, *Astron. and Astrophys.* **115** (1982) 357;

    R. Rebolo, P. Molaro and J. Beckman, *Astron. and Astrophys.* **192** (1988) 192;

    L. Hobbs and C. Pilachowski, *Astrophys. J.* **326** (1988) L23.

27. G. Steigman, D.N. Schramm and J. Gunn, *Phys. Lett.* **66B** (1977) 202.

28. V.F. Schvartzman, *JETP Letters* **9** (1969) 184;

    P.J.E. Peebles, *Physical Cosmology* (Princeton University Press, 1971).

29. D.N. Schramm and L. Kawano, *Nuc. Inst. and Methods* A **284** (1989) 84.

30. B. Pagel, *Proc. of 1989 Rencontre de Moriond*

31. R. Scherrer, J. Applegate and C. Hogan, *Phys. Rev. D 35* (1987) 1151;

    C. Alcock, G. Fuller and G. Mathews, *Astrophys. J.* **320** (1987) 439;

    W.A. Fowler and R. Malaney, *Astrophys. J.* **333** (1988) 14.

32. H. Kurki-Suonio, R. Matzner, K. Olive and D.N. Schramm, *Astrophys. J.* **353** (1990) 406;

33. M. Peimbert and S. Torres-Peimbert, *Astrophys. J.* **193** (1974) 327.

34. B. Pagel, *ESO/CERN Proc.* (1990).

35. G. Steigman, D.N. Schramm and J. Gallagher, *Comments on Astrophys.* **14** (1989) 97.

36. W. Mampe, P. Ageron, C. Bates, J.M. Pendlebury and A. Steyerl, *Phys. Rev. Lett.* **63** (1989) 593.

37. J. Byrne, *et al. Phys. Lett. B*, submitted (1990).

38. H. Abele, M. Arnould, H.A. Borel, J. Dohner, D. Dubbers, S. Freedman, J. Last and I. Reichert, *Proc. Grenoble Workshop on Slow Neutrons* (1989).

39. G. Steigman, K. Olive, D.N. Schramm and M. Turner, *Phys. Lett. B* **176** (1986) 33.

40. ALEPH, DELPHI, L3, OPAL and MARK II collaboration papers in *Proc. of the Int. High Energy Conference, Singapore* (1990).

41. D.N. Schramm and G. Steigman, *Phys. Lett. B* **141** (1984) 337.

42. E. Kolb and R. Scherrer, *Phys. Rev. D* **25** (1982) 1481;

A. Chakravorty, E. Kolb and D.N. Schramm, in progress (1990).

43. S. Dimopoulos, R. Esmailzadeh, L. Hall and G. Starkman, *Astrophys. J.* **330** (1988) 545.

44. L. Brown and D.N. Schramm, *Ap.J.* **329** (1988) L103.

45. C. Pilachowski, L. Hobbs and D. De Young, *Ap.J. Lett.* 345 (1989) L39.

46. H. Reeves, K. Sato and M. Tarasawa, U. of Tokyo preprint (1989).

N. Tarasawa and K. Sato, U. of Tokyo preprint (1990).

47. C. Alcock, G. Fuller, G. Mathews, and B. Meyer, Livermore preprint (1990).

48. F. Adams and K. Freese, MIT preprint (1990)

49. L. Kawano, W. Fowler and R. Malaney, Caltech-Kellogg preprint (1990).

J. Applegate, Columbia University preprint (1989).

50. K. Freese and D.N. Schramm, *Nucl. Phys.* **B233** (1984) 167.

51. M. Strauss, M. Davis and A. Yahil, U.C. Berkeley preprint (1989);

N. Kaiser and A. Stebbins, CITA preprint (1990);

E. Bertschinger, A. Dekel, and A Yahil, *Proc. Blois Symposium on the Microwave Background* (1990);

M. Rowan-Robinson and A. Yahil, *Proc. Rencontres de Moriond* (1989).

52. A. Guth, *Phys. Rev. D* **23** (1981) 347; see also K. Olive, *Physics Reports* **190** (1990) 309-403 or A. Lindei, *Particle Physics and Inflationary Cosmology* (NY: Harwood, 1990).

53. D. Hegyi and K. Olive, *Astrophys. J.* **303** (1986) 56.

54. J. Gunn, Talk at ITP Santa Barbara (1988);

D. York, Talk at University of Chicago (1988).

55. G. Mathews and D.N. Schramm, *Astrophys. J.*, submitted (1990).

56. L. Cowie, *Proc. IUPAP Conference on Primordial Nucleosynthesis and Evolution of Early Universe, Tokyo, September 1990*, in press (1990).

57. R. Bond and A. Szalay, *Proc. Texas Relativistic Astrophysical Symposium, Austin, Texas* (1982).

58. M. Turner, F. Wilczek and A. Zee, *Phys. Lett. B* **125** (1983) 35; **125** (1983) 519.

59. M. Crawford and D.N. Schramm, *Nature* **298** (1982) 538.

E. Witten, *Phys. Rev. D* **30** (1984) 272.

See also C. Alcock and A. Olinto, *Ann. Rev. Nuc. Part. Phys.* 38 (1988) 161.

60. Ya. Zeldovich, *Adv. Astron. and Astrophys.* 3 (1965) 241.
61. B. Lee and S. Weinberg, *Phys. Rev. Lett.* **39** (1977) 165.
62. H-Y. Chiu, *Phys. Rev. Lett.* **17** (1966) 712.

    C.P. Hut, *Phys. Lett. B* **69** (1977) 85;

    K. Sato and H. Koyayashi, *Prog. Theor. Phys.* **58** (1977) 1775.
63. S. Dimopoulos, R. Esmailzadeh, L. Hall and N. Tetradis, *Nucl. Phys. B*, submitted (1990).
64. D. Brahm and L. Hall, *Phys. Rev. D* **41** (1990) 1067.
65. K. Griest, M. Kamionkowski and M. Turner, FNAL preprint (1990).

    K. Olive and M. Srednicki, *Phys. Lett. B* **230** (1989) 78.
66. D. Caldwell, *et al.*, *Proc. La Thuile*, ed. M. Greco (1990); see also Kamiokande II Collaboration, Proc. IUPAP Sumposium on Primodial Nucleosynthesis and Evolution of Early Universe, Tokyo, September 1990, in press (1990).
67. L. Krauss, *Phys. Rev. Lett.*, in press (1990);

    K. Griest and J. Silk, U.C. Berkeley preprint (1990).
68. J. Ellis, D. Nanopoulos, L. Roskowski and D.N. Schramm, *Phys. Lett. B*, in press (1990).
69. D. N. Schramm, *Proc. 1988 Berkeley Workshop on Particle Astrophysics*, ed, E. Norman (World Scientific, 1989).
70. S.M. Faber and J.S. Gallagher *Ann. Rev. Astron. and Astrophys.* **17**, 135 (1979).
71. E. Loh and E. Spillar, *Astrophys. J.* **329** (1988) 24.
72. C. Hill, D. Schramm and J. Fry, *Comments Nucl. Part. Phys.* **19** (1989) 25.

    D. Schramm, *Proc. IUPAP Symposium on Primordial Nucleosynthesis and Evolution of Early Universe, Tokyo, September 1990*, in press (1990).
73. SAGE collaboration *Proc. Int. High Energy Physics Meeting, Singapore, August 1990*, in press (1990).